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Research

Adaptive pathways and coupled infrastructure: seven centuries of adaptation to water risk and the production of vulnerability in Mexico City

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ABSTRACT. Infrastructure development is central to the processes that abate and produce vulnerabilities in cities. Urban actors, especially those with power and authority, perceive and interpret vulnerability and decide when and how to adapt. When city managers use infrastructure to reduce urban risk in the complex, interconnected city system, new fragilities are introduced because of inherent system feedbacks. We trace the interactions between system dynamics and decision-making processes over 700 years of Mexico City's adaptations to water risks, focusing on the decision cycles of public infrastructure providers (in this case, government authorities). We bring together two lenses in examining this history: robustness-vulnerability trade-offs to explain the evolution of systemic risk dynamics mediated by feedback control, and adaptation pathways to focus on the evolution of decision cycles that motivate significant infrastructure investments. Drawing from historical accounts, archeological evidence, and original research on water, engineering, and cultural history, we examine adaptation pathways of humans settlement, water supply, and flood risk. Mexico City's history reveals insights that expand the theory of coupled infrastructure and lessons salient to contemporary urban risk management: (1) adapting by spatially externalizing risks can backfire: as cities expand, such risks become endogenous; (2) over time, adaptation pathways initiated to address specific risks may begin to intersect, creating complex trade-offs in risk management; and (3) city authorities are agents of risk production: even in the face of new exogenous risks (climate change), acknowledging and managing risks produced endogenously may prove more adaptive. History demonstrates that the very best solutions today may present critical challenges for tomorrow, and that collectively people have far more agency in and influence over the complex systems we live in than is often acknowledged.

Key Words: *adaptation; flooding; infrastructure; robustness; urban social-ecological systems (SES); vulnerability; water scarcity*

INTRODUCTION

Managing risk in the urbanizing Anthropocene is one of the greatest challenges and opportunities of the twenty-first century. The concentration of people, as well as social, cultural, economic, and infrastructural capital in cities means that they are especially vulnerable to catastrophic loss and failure from diverse shocks and stressors, from severe weather to human migration. Infrastructure, the structures and facilities that enable systems to function, is central to the abatement and production of vulnerabilities. Cities are built systems, relying on both hard infrastructure (e.g., the built environment) and soft infrastructure (e.g., policies, programs, knowledge, and social relations) to mediate social-environmental interactions, particularly environmental risks. Insights from systems and complexity science demonstrate that adaptations, i.e., efforts to enhance system robustness to threats, inevitably produce new fragilities and vulnerabilities (Csete and Doyle 2002, Anderies 2015*a*, Carpenter et al. 2015). Similarly, findings from interdisciplinary social science and political economy research have concluded that endogenous social processes contribute to vulnerability (Adger and Kelly 1999, McLaughlin and Dietz 2008). Nevertheless, facing increased uncertainty, heightened environmental variability, and accelerated change, urban decision makers and scholars tend to view urban vulnerability as the product of exogenous stressors.

We argue that how urban actors (especially those with power and authority) perceive, interpret, and respond to vulnerability is a critical endogenous driver of system dynamics, which shapes and reshapes vulnerability and robustness to new and existing threats over time. Urban decision makers' responses to emergent threats can contribute to the vulnerability of their cities, even as they strive to mitigate risks. The effects of these actors' responses to system dynamics, robustness, and vulnerability are made apparent through analysis of long-term adaptation pathways, consisting of events, decisions, and actions. As cities adapt to twenty-first century challenges, it is imperative to understand how system dynamics and human agency have interacted over time to define the contours of adaptation pathways today. These pathways will, in turn, build or constrain resilience tomorrow. Although the term "resilience" is often used in a normative sense when applied to an urban context (Fernández et al. 2016, Meerow et al. 2016), we use the term to describe a system state. For clarity, we define the key terms we use in Table 1 and refer to other sources for in-depth discussions of these concepts (Wisner et al. 1994, Turner 2010, Anderies et al. 2013).

We trace the interactions between system dynamics and decision-making processes through 700 years of Mexico City's adaptations to water risks, focusing on the decision cycles of government authorities. Decision cycles (see Table 1) include the factors that shape which adaptation options are considered, how a decision is made, and the immediate consequences that decision produces, which inevitably shape subsequent pathways of adaptation, and thus lead into the next decision cycle (Wise et al. 2014). The

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Table 1. Key concepts, definitions, and references. SES = social-ecological systems.

Key Term	Definition	Key Reference
Vulnerability	Propensity for loss when exposed to a threat.	(White 1974, Turner et al. 2003)
Resilience (applied to SES, also known as general resilience)	Ability of a system to respond to disturbance, to self-organize, and to learn or adapt.	(Folke et al. 2002)
Robustness (known as specific or engineering resilience)	Ability of a system to perform within a range of variance.	(Anderies et al. 2013)
Feedback control	A concept developed mainly in engineering, feedback control in an SES represents how a controller (decision makers in an SES) may influence the coupled infrastructure system (the “plant” in engineering). The controller measures system outcomes, evaluates them against system performance goals, makes decisions, and provides a signal (action) that feeds back into the plant, generating new outcomes and thus beginning a new decision cycle.	(Anderies 2014a)
Adaptation	Adjustment to change in the physical, social, or economic environment.	(Denevan 1983)
Decision cycle	The process of receiving information about threats to the system, weighing potential responses, making a choice, and evaluating the consequences of that decision.	(Wise et al. 2014)
Adaptation pathway	A series of decision cycles over time that represent the trajectory of adaptation in an SES.	(Wise et al. 2014)
Infrastructure	Structures that facilitate the ability to produce mass and information flows that humans value.	(Anderies et al. 2016)
Risk	Probability and magnitude and magnitude of the consequences of a threat, given system vulnerability.	(Turner et al. 2003)
Threat	A perturbation, stress, hazard, or shock that could cause loss or harm because it is beyond the normal range of variability in the system. A threat could be biophysical (e.g., rain storm, earthquake) but also includes endogenous and human caused sources of perturbation or stress (e.g., failure of a flood pump).	(Turner et al. 2003)

decision cycle itself can span months or even years, depending on the extent of planning and investment necessary prior to any action, and the temporal legacy of the decision's impact (Stafford Smith et al. 2011). Our analysis highlights decisions in the Basin of Mexico that transformed the function and structure of the biophysical, social, and/or economic nature of the SES, or that further entrenched an existing adaptation pathway. The path dependency created by these consecutive decision cycles ultimately constrains, and in some cases, determines a particular approach to water management in Mexico City.

We bring together two lenses to examine this history. We leverage the concept of robustness-vulnerability trade-offs (Anderies 2015*b*) to understand how feedbacks between system interventions to reduce risk can produce new vulnerabilities. We combine this concept with that of adaptation pathways (Wise et al. 2014), which focuses on the evolution of decision cycles that motivate significant infrastructural investments. Using these two lenses and drawing from historical accounts, archeological evidence, and original research on water, engineering, and cultural history, we illustrate how threats that urban managers initially perceived as exogenous became endogenous as the city adapted to risk and grew in size and complexity. These threats emerge dynamically in concert with decision makers' efforts to control risk and to maintain their authority in contexts of diverse political, environmental, and economic pressures.

We are not the first to tell the story of Mexico City and the management of its surrounding basin (Palerm 1973, Sanders et al. 1979, Ezcurra et al. 1999, Gayon Cordova 2000, Castro 2006, Connolly 2007, Candiani 2014). Nevertheless, we argue that reinterpreting the well-known narrative of Mexico City's social and hydrological development through these lenses provides insights into contemporary debates on the elusive but imperative pursuit of urban resilience and sustainability. The insights yielded by this approach are particularly relevant as cities today adapt to threats related to climate change, such as water shortages, flooding, drainage, and other challenges (Muller 2007, Hunt and Watkiss 2011, Leichenko 2011). By examining how the interplay of system dynamics and human agency jointly shape the trajectory of urban development and patterns of vulnerability in Mexico City, we can begin to address critical questions:

- How do urban systems adapt to environmental risks over the long term?
- What do city managers learn from the consequences of past actors' approaches to confronting environmental risks?
- In key decision points, what environmental processes were being addressed and why at those moments in time?
- When and under what circumstances do environmental extremes, i.e., moments of significant disturbance, mobilize actions and interventions?
- What is the role of social and political factors in these decision cycles?
- Which decisions shape path dependency and what are the consequences?

THEORETICAL BACKGROUND

Vulnerability, resilience, and robustness in cities

As complex adaptive systems, cities exhibit emergent properties, nonlinear development trajectories, and feedback mechanisms in which the built environment and material flows are coupled with culture, economic processes, social organization, and decision making (Ernstson et al. 2010). Despite the best attempts to order social interaction through urban planning, cities are hard to manage: their structure and function emerge from multiple interactions across scales, subsystems, and the dispersed geographies from which resources are drawn, while their boundaries are fluid and elusory (Boone et al. 2014, Henderson et al. 2016). In contrast to natural systems, urban systems heavily rely on the construction and maintenance of built, human-made, and often publicly funded infrastructure. This infrastructure, which may be either soft (e.g., policy) or hard (e.g., roads, pipes, and bridges), mediates interactions with the natural environment. The defining role of built public infrastructure in urban systems suggests the utility of framing cities as coupled infrastructure systems (CIS), which are a general class of systems analogous to social-ecological systems, but in which infrastructure dynamics are recognized as playing an important role mediating interactions (Anderies et al. 2016).

The CIS framework outlines system components and interactions among five types of infrastructure: (1) human (knowledge), (2) social (social relations), (3) natural (ecosystems), and previously discussed (4) soft and (5) hard (built) infrastructure. One important insight developed from applying this framework, originally in irrigation systems, (Anderies 2006, Cifdaloz et al. 2010, Yu et al. 2015) is that human efforts to manage environmental variance through different hard and soft infrastructures result in robustness-vulnerability trade-offs (Csete and Doyle 2002, Chandra et al. 2011, Anderies and Janssen 2013, Anderies 2015*b*). Investing in hard infrastructure to make a system robust to a specific risk, such as building levees to protect a city from flooding, tends to increase the material rigidity in the system, which may result in emerging vulnerabilities that are hidden until the system fails. Though this insight is not new (see White 1945 on the "levee effect" and flood risk), humans continue to manage environmental variance with hard infrastructure, driven by the goal of reducing risk in the immediate and short term. However, the resulting reduced flexibility tends to increase vulnerability of the system in the long term (Carpenter et al. 2015). The concept of robustness-vulnerability trade-offs has been applied in several archaeological cases and rural CIS (Hegmon et al. 2008, Cifdaloz et al. 2010, Nelson et al. 2010). The lessons learned from these cases underscore the costs of resilience and the impossibility of eliminating vulnerability (Schoon et al. 2011). Eliminating vulnerability becomes even more untenable in an urban context. Research on resilience asserts that vulnerability to a new kind of risk can increase as systems become increasingly interconnected (Holling 2001) or head toward collapse (Tainter 1990) and renewal in the adaptive cycle (Gunderson and Holling 2002). However, instead of collapsing, today's globalized and interconnected urban conglomerates continue to adapt by transferring large amounts of resources and information over long distances, connecting urban populations and decision making to resource dynamics in distant places (Seto et al. 2012, Liu et al. 2013).

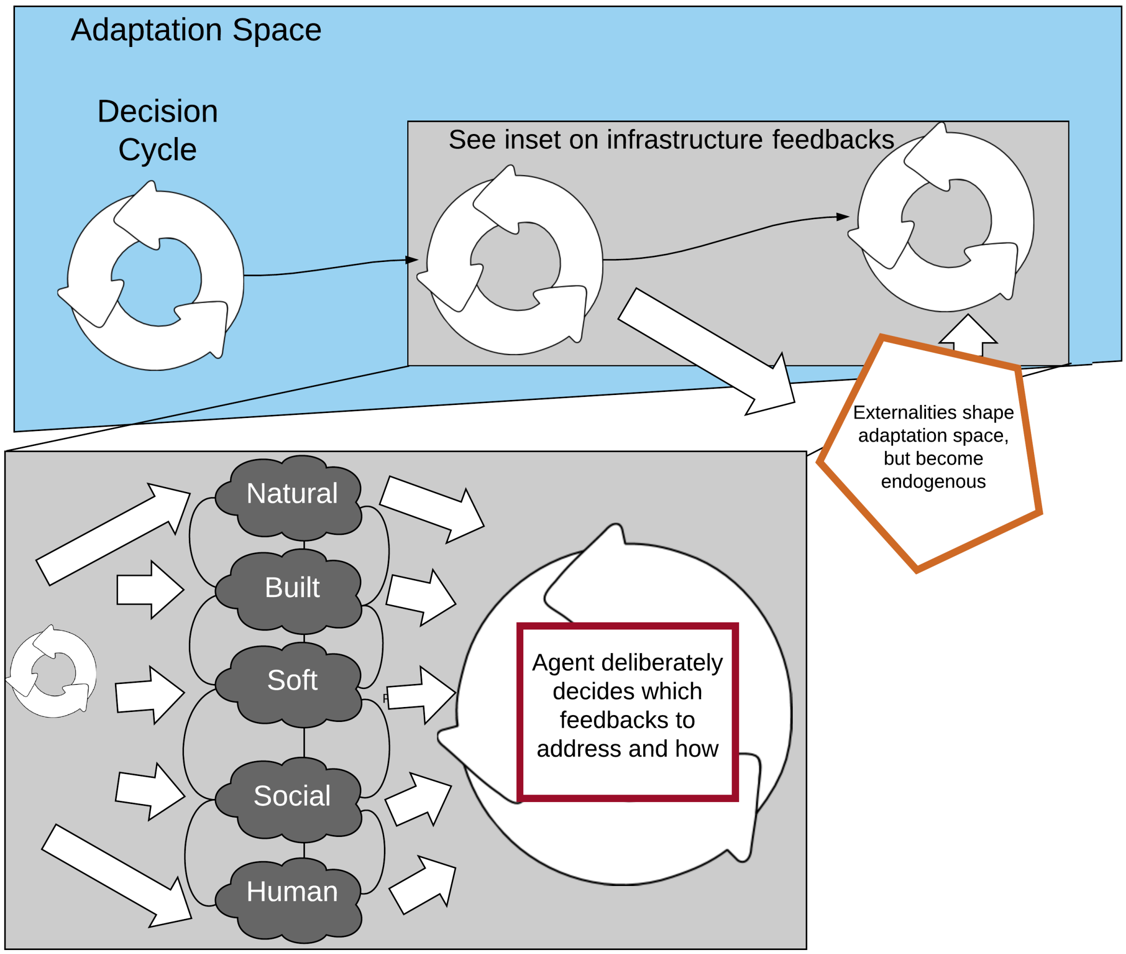
Although city managers may assume their actions mitigate vulnerability for the city as a coherent system, we know from history that they often prioritize specific populations. Mitigating the vulnerability of one population, or to one type of threat can have unintended consequences in highly connected cities. The uneven distribution of human agency in coupled infrastructure systems (Davidson 2010, Brown and Westaway 2011) ensures that human efforts to enhance robustness are guaranteed to benefit some groups more than others and reflect particular visions of risk. As human-dominated systems, cities are shaped by the volition, intention, and agency of influential social actors and groups (Davidson 2010, Manuel-Navarrete 2015). Human decision-making dynamics dominate how such systems adapt and respond to environmental stress in ways that can mitigate or produce vulnerability, and influence the manifestation of resilience and robustness in a city (Romero Lankao and Qin 2011, Eakin et al. 2017). Over time, such decisions result in development pathways that shape the evolution of the CIS. Thus, to understand change in urban systems more fully, we combine the concept of robustness-vulnerability trade-offs with the adaptation-pathways approach, which focuses on human agency and drivers of adaptation decisions.

Decision cycles in human dominated coupled infrastructure systems (CIS)

Although there are some remarkable historical examples (Diamond 2005), cities of the modern era have rarely been known to collapse. As cities grow in terms of space, economy, and resource consumption, they are forced to endogenize what were once external risks and respond to new external threats. Thus, rather than conceptualize urban change as cycles of nonlinear growth and renewal across scales (Holling 2001), we apply the concept of adaptation pathways (Leach et al. 2007, Haasnoot et al. 2013, Wise et al. 2014). People create and shape these pathways through power relations and decisions: both small, incremental decisions leading toward a larger goal, and decisions to enact significant interventions with long "decision lifetimes" (i.e., the sum of the lead times and consequence times; or, how long it takes to prepare for and gather information to make a decision, and how far into the future the impact of the decision lasts; Smith et al. 2011, Wise et al. 2014). Major decisions warrant emphasis and analysis because they shape the system's adaptation pathway and may fundamentally alter the system. In the urban environment, decision cycles center around major public infrastructure investment decisions. In our analysis, a decision cycle begins with an event, such as a natural disaster, a political opportunity (an election, a celebration), or new information, which highlights risk or vulnerability, thus eliciting a response from actors, in this case urban authorities. The actors first seek information to decide how best to mitigate risk. What kind of information they seek, and how they evaluate it, will depend on the dominant frames and narratives at that moment in history, shaped by past decision cycles. The cycle ends after the determined action is implemented. The consequences of the action taken in a given decision cycle will shape the options available in the next cycle, because it sets the development pathway that ensues. In other words, decision cycles are embedded in the cultural, political, environmental, economic, and developmental contexts of the moment, but are heavily determined by the decision cycles that preceded them and will shape the decision cycles that follow. In urban CISs, the decision pathways that tend to increase soft and hard infrastructure, staffed by people who could lose their jobs, becomes self-reinforcing. Positive feedbacks, path dependency, and system inertia, i.e., fundamental features of any social-ecological system, put CISs at risk of lock-in or a rigidity trap (Schoon et al. 2011, Wise et al. 2014).

Adaptations are not simply technical responses to environmental feedbacks. Rather, they are conditioned by policy, norms, and social relations, which are filtered through political processes,

Fig. 1. Coupled infrastructure pathways. A series of decision cycles create an adaptation pathway. In each cycle, an agent (or agents) makes deliberate adaptation decisions that selectively respond to changes in the coupled infrastructure system driven by the previous decision cycle. In an urban system, some adaptations have spatial or system externalities, which in turn influence the degree of choice available at any moment of time (the adaptation space). These externalities may even become endogenous as the city grows in space and complexity. Figure inspired by Wise et al. (2014) and Anderies (2015*b*).



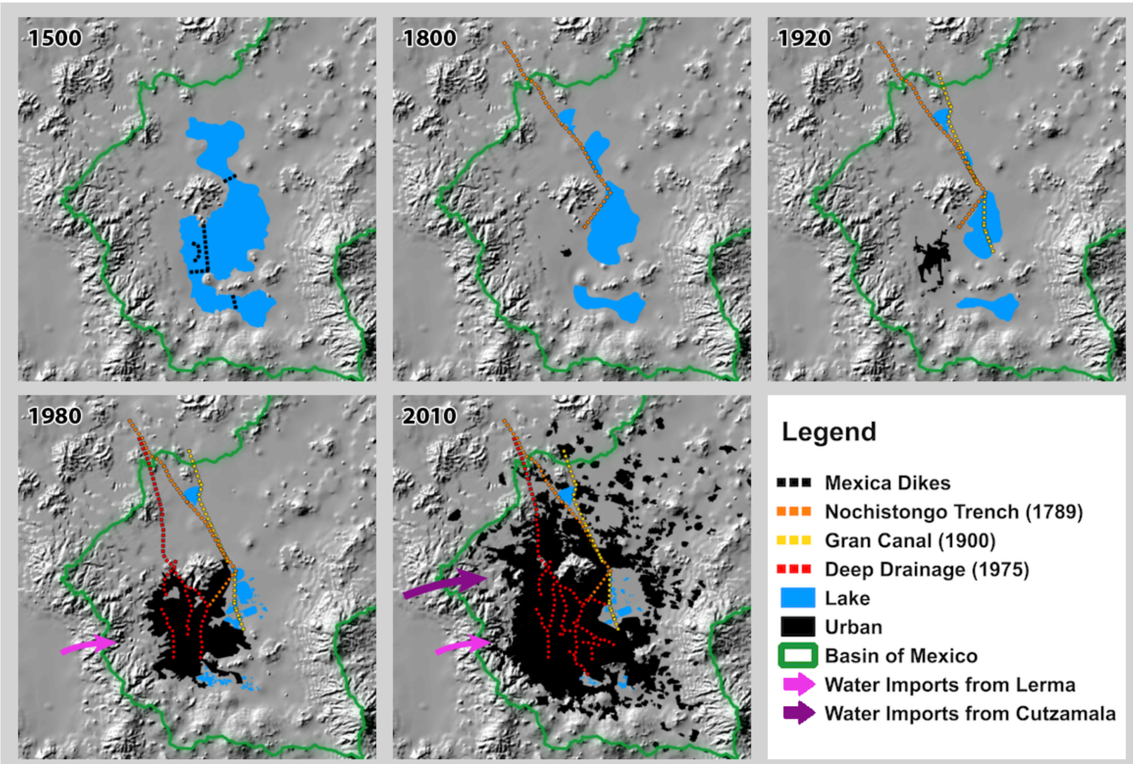
governance arrangements (Eriksen and Lind 2009, Eriksen et al. 2015), and power (Avelino and Rotmans 2009). Adaptation is part of the governance process through which stakeholders come together to exchange information and make decisions. In these situations, power dynamics among actors shape the dominant narrative on vulnerability to define the threat, which factors produce the threat, who or what is vulnerable, and which response options are available or desirable. How vulnerability is defined, and by whom, can have a large impact on subsequent decisions (Wise et al. 2014).

The concept of adaptation pathways emphasizes the social dynamics and the human agency in adaptation, deemphasizing the biophysical and environmental feedbacks that each decision may produce. However, when combined with a resilience and robustness lens that emphasizes the constraints that biophysical and environmental feedbacks impose on human agency, adaptation pathways help explain the core role of urban infrastructure in creating vulnerabilities over the long term.

Coupled infrastructure pathways

Combining the insights regarding robustness vulnerability trade-offs and adaptation pathways, we posit that it is the combination of system dynamics and feedbacks, mediated by hard and soft infrastructure, with decision-making processes that influence the future trajectories of cities as a CIS. This coupled infrastructure pathways approach is useful for understanding urban adaptation by highlighting: (1) the temporal dynamics of human agency and (2) how biophysical feedbacks, modulated by public infrastructure, influence adaptation choices and path dependency. In other words, a pathways approach illustrates how social dynamics modulate a system's response to disturbance and situates these dynamics in their historical trajectory (see robust feedback control in Csete and Doyle 2002, Anderies 2014). Figure 1 represents this conceptual approach. By combining the two approaches, we can illuminate how the feedbacks resulting from decision cycles can create, reinforce, or mitigate vulnerability for the system as a whole and for specific subpopulations and places

Fig. 2. Transformation of the Basin of Mexico over time, via urban expansion, draining lakes, and investments in built infrastructure 1500-2010. Infrastructure data: Tellman hand-drew and georeferenced the Mexica Dikes and Nochistongo Trench from map by Jorge Guerria Lacroix (DDF 1975); Drainage 1920-2010 from SACMEX*a*; Urban and Lake Areas courtesy of Centro Eure based on data from GEM 1993, INEGI 1980, 2000.



within a complex system. As cities grow and invest in infrastructure over time, system dynamics produce feedbacks that reverberate across adaptation pathways. This means that interconnected risks must be managed in concert with a long-term perspective. Failure to do so, as we illustrate in Mexico City, can prove maladaptive for one or more of the interconnected risks. Examining robustness-vulnerability trade-offs helps conceptualize these connections.

COUPLED INFRASTRUCTURE PATHWAYS IN MEXICO CITY

Mexico City is located within the Basin of Mexico, a high plains area (2240 masl) that encompasses the capital city and surrounding states of Mexico, Hidalgo, Tlaxcala, and Puebla. Surrounded by mountain ranges with no natural outlet, the basin's topography caused the natural formation of five shallow lakes, three saline and two freshwater, covering 1500 km² of the basin floor before being drained. Recharge of the basin's aquifer occurs on naturally forested slopes in the upper elevations of the watershed, and the lower watershed's lacustrine clay soils, on which Mexico City was built, are highly compressible and form an aquitard (Marsal and Mazari 1962, Ezcurra et al. 1999, Bojórquez Tapia et al. 2000). Over the past 700 years, Mexico City has grown from a metropolis of 1 million inhabitants to a megalopolis of over 22 million. Throughout this period, it has remained the region's (and eventually became the nation's) political, economic, cultural, and industrial capital. This growth significantly altered the natural infrastructure that regulates flooding and provides drinking water to the city's inhabitants. Since the city was founded, its political leaders and engineers have successively replaced natural infrastructure with human-made public infrastructure, both hard (e.g., pipes, pumps, drains, and dams) and soft (e.g., governance mechanisms) to adapt to increasing water risks (see Fig. 2).

The transformation of the Basin of Mexico, and the persistence of the city itself, results from key decisions to manage urban growth, water supply, wastewater management, and flood risk. We examine the major decision cycles that have defined the basin's trajectory and refer to other sources for more details of its complex history. Each decision to adapt occurs in a context shaped by previous decisions. Thus, the city's adaptation to water risks is best understood as a series of consecutive decision cycles that defines an adaptation pathway, which constrains or determines future decisions. We trace the history of Mexico City's adaptation on three distinct pathways: human settlement, drinking water, and flood risk management. We illustrate how these distinct adaptation pathways have become increasingly path dependent and interconnected as the city has grown in population, area, and complexity, and how the robustness-vulnerability trade-offs of urban decision makers' responses to risk emerge with ever-greater consequences over time.

Human settlement pathway

Mexico City's history begins with the Mexica, the eventual military leaders of the Aztecs, a coalition of powerful indigenous groups in the Basin of Mexico that administered a complex network of trade routes, markets, tributary provinces, and social authority (Gibson 1964, Escalante Gonzalbo 2013). In 1325, the Mexica made the pivotal decision to construct their citadel on an island in the middle of a shallow, saline lake, with limited access to clean drinking water and, as they soon learned, frequent exposure to flooding. The Mexica's motivation for locating their capital, México-Tenochtitlán, on this island is debated. They may have been influenced by its defensive advantages (Lombardo de Ruiz 2000), transport, food resources, and other natural infrastructure (Parsons 2006), or a combination of factors. Religion may have also played a role: according to legend, the god Huitzilopochtli told the Mexica they should settle in the place in which they saw an eagle perched on a nopal cactus with a snake in its mouth; this vision was realized on the island of Tenochtitlán (Castañeda de la Paz 2005). Whatever their motive, this decision set in motion an adaptive pathway that led the Mexica to develop a thriving city on the island, with impressive infrastructure. To feed the growing urban population, they expanded the *chinampa* agricultural system, a highly productive wetland agroecosystem (Armillas 1971). They built dikes, sluices, and aqueducts to bring freshwater in and keep saline water out (Parsons 1976, Pozo 2010, Morehart and Frederick 2014). However, to secure their access to freshwater and other resources, they violently dominated neighboring lords and tribute-paying populations (Gibson 1964, Ezcurra et al. 1999, Knight 2002).

The second critical decision cycle for human settlement began with the Spanish Conquest in 1521. The Spanish *conquistadores*, the basin's new leaders led by Hernán Cortés, were aware of the difficulties posed by Tenochtitlán's location (García Acosta et al. 2003) and saw limited value in the chinampa farming system, the basis of Tenochtitlán's subsistence (García Martínez 2004). Political considerations prevailed, however: instead of founding the Spanish capital on more solid ground, Cortés decided to build the capital of New Spain on top of Tenochtitlán's ruined pyramids for its defensive advantages and political symbolism, to establish dominance in the region (Lombardo de Ruiz 2000). The full environmental implications of this decision only became apparent to the colonial authorities some three decades later: the Spanish had destroyed much of the Mexica's built hydrological infrastructure during the conquest. Because they did not understand these works, they failed to maintain them. A major flood devastated the city in 1555 (García Martínez 2004, Castro 2006).

A second flood struck in 1556, marking the beginning of a third major decision cycle. In response, the colonial authorities considered relocating the capital. They decided it would be too expensive to resettle the city and stayed (DDF 1975). This decision led to a century of urban expansion and modification of the Basin of Mexico to suit the economic priorities of the Spanish and maintain socio-cultural and political dominance. The colonizers relied on horses for transport, not canoes; they relied on the haciendas of the Puebla and Lerma valleys for food, not chinampas. They deforested the hills to supply wood for colonial constructions, including water-supply infrastructure (Aguilar Santelises et al. 1997). The deforestation caused erosion, which filled transport canals and lakes with sediment. This raised lake levels, increased runoff, diminished groundwater infiltration, and exacerbated flooding (Domínguez Mora 2000).

A fourth decision cycle was provoked in 1629 by another devastating flood, which killed 30,000 people and lasted five years (García Martínez 2004, Candiani 2014). About 50,000 residents abandoned the city. The colonial authorities debated relocating the capital again, and decided to stay yet again, citing tradition, religion, patriotism, and economic losses for the church and wealthy if the city were relocated (García Martínez 2004).

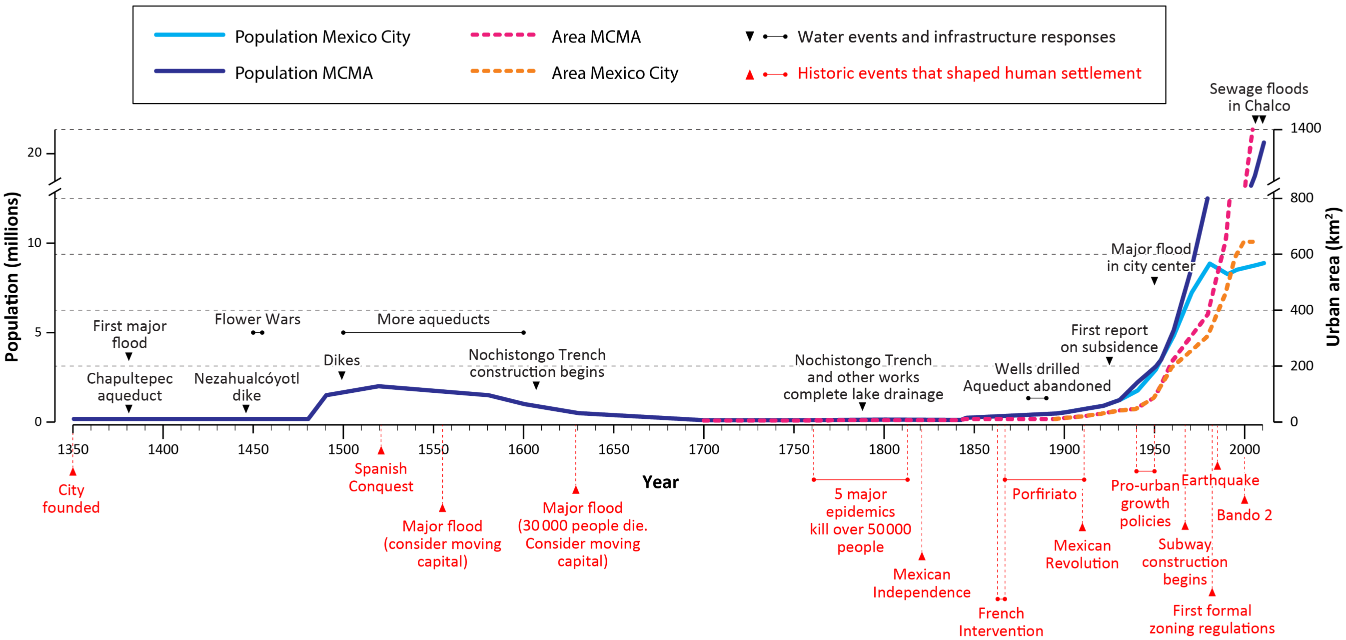
Throughout the colonial period, the city was struck by frequent epidemics of typhus and smallpox that afflicted all orders of society: the working class, the indigenous, and religious and economic elites (Cooper 1965, Acosta 1993, McCaa 2000, García Acosta et al. 2003). These events reinforced residents' and decision makers' negative perception of water and their desire to drain the basin's lakes (Cooper 1965, Agostoni 2003). To improve public health, which remained a challenge even following the introduction of vaccines in 1803, sanitation became an increasingly pressing concern. However, the city was sinking into the soft lacustrine soils under the weight of its heavy colonial buildings, which exacerbated drainage and flood problems (Martínez 1980 as cited by Connolly 2007).

In 1886, a fifth decision cycle began when national leaders prepared Mexico City to host Mexico's centennial celebration, during which foreign dignitaries would bear witness to Mexico's arrival as a modern nation. City managers decided to combined storm and sanitary drains to evacuate stagnating human waste from the subsiding city through the *Gran Canal* (Great Canal). The canal was to be a permanent solution to both flood and sanitation issues by exporting Mexico City's wastewaters and lake water out of the basin (Agostoni 2003). The drained lakebeds enabled urban expansion, accelerated by national industrialization policies and land reforms following the Mexican Revolution in 1910-1929 (see Figs. 2, 3; Cruz Rodríguez 1995, Davis 2010).

In the sixth decision cycle, urban managers responded to the dramatic urbanization of the 1930-60s, which was driven directly and indirectly by national and city-level economic and land-use policies. To address the consequences of this expansion, the urban government regularized illegal settlements and developed the public subway system, which further facilitated urban growth (Davis 2010). Major housing projects (e.g., Miguel Alemán and Tlatelolco, which housed 80,000 people in over 100 buildings by 1985) were constructed during this time (Davis 2010). However by the late 1970s, poor air quality, subsidence, and deteriorating water infrastructure led officials to attempt to control urban growth and densify the central city with new soft infrastructure, such as laws, public agencies, and programs to regularize informal settlements and expand housing credit (Connolly 2007, Schteingart and Salazar 2010).

A seventh decision cycle began in the late 1970s, as the city experienced terrible air quality and declining water resources caused by the city's growing population, traffic, and industrialization. Decision makers first proposed a "Conservation Zone" (*Suelo de Conservación*) in 1978 to protect the city's watershed and improve air quality. Approved in 1992, the zone comprises 59% of Mexico City proper (Connolly 2007,

Fig. 3. Urban area and population growth in Mexico City proper and the larger metropolitan area (MCMA is Mexico City Metropolitan Area), 1325 to present, with significant historical events and adaptation decisions. Note: population estimates for the metropolitan area represent the population in the Basin of Mexico until 1521. Separate population data for Mexico City and the MCMA were not available until the 1960s. Note: break in scale for metropolitan area population and urban area in the 1990s, which grew exponentially. Sources: Sanders et al. 1979, Ezcurra et al. 1999, Negrete-Salas 2000, Scheingart and Salazar Cruz 2010.



Sheinbaum Pardo 2008). However, these policies only increased land prices and paradoxically expanded the metropolitan area by pushing the poor further outside the city's boundaries into the State of Mexico, where urbanization rates today are as high as 2% annually (see Fig. 3). Water scarcity, flooding, and uncontrolled urban expansion continue to plague the city's development and increasingly require interstate coordination to address the burgeoning resource demands of the more than 22 million people living in the metropolitan area.

Water supply pathway

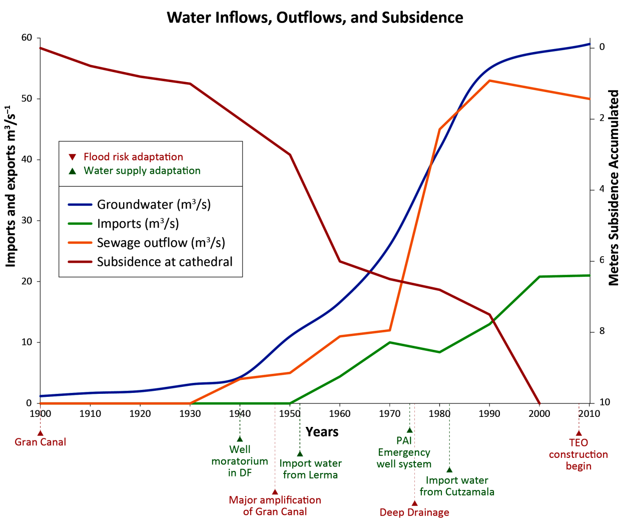
The Mexica knew that settling in the saline lacustrine environment would entail importing fresh spring water from their neighbors; water imports continue to constitute 30% of the city's supply today. The first decision of this pathway was to build the city's first wooden aqueduct in 1381, to deliver water from the springs of Chapultepec. Relying on other communities' freshwater resources required investments in physical and social infrastructure, especially political relations, making the city vulnerable to both social conflict and hard infrastructure failures. Water scarcity and occasional drought triggered aggressive military campaigns, exemplified by the bloody Flower Wars (*Guerras Floridas*) of 1450-1455. In the late fifteenth century, the Mexica leader Ahuizotl expanded on this pathway, deciding to import water from the springs of Coyoacán and Churubusco (Huitzilopochco) to raise the declining levels of freshwater in Lake Mexico. Ahuizotl refused to hear warnings from Tzotzoma, Coyoacán's leader, that the powerful springs would flood Tenochtitlán, and executed him for insubordination. In 1499, the aqueduct indeed overflowed, devastating the city. The Mexica leaders then sealed the spring, and reconstructed and elevated the city as well as the Nezahualcóyotl Dike (Legorreta Gútierrez 2006). This would not be the last time that a leader's attempt to increase robustness of the water supply against local advice would prove maladaptive and increase the city's flood risk.

The second decision cycle was marked by the political transition to Spanish colonial rule, during which the city's decision makers followed the Mexica's strategy of subjugating the indigenous communities within the watershed to gain access to their spring water supplies and to reconstruct aqueducts to deliver water to the city. However by 1870, the volume of spring water was insufficient to meet the growing city's demand (Gayon Cordova 2000), and the ancient aqueducts were obstructing the development of the modern transport system.

This impasse led to the third decision cycle at the end of the 1800s, in which urban authorities decreased investment in public water infrastructure, and elites increased investment in private groundwater wells to supplement the surface water supply (Castro 2006, Legorreta Gútierrez 2008). The adaptation pathway then shifted as urban authorities and residents embraced groundwater as the city's primary water source, aided by advancements in pumping technology. Although groundwater extraction helped meet the water demands of the growing population, it accelerated subsidence, despite watershed conservation efforts.

In the mid 1920s, the fourth decision cycle commenced with early reports from prominent experts linking subsidence to groundwater extraction (Carrillo 1969). This knowledge, however, was initially ignored and groundwater pumping increased until the 1940s (Marsal and Mazari 1962, Marsal 1992). Subsidence rates increased to 18 centimeters per year from 1930-1960, damaging the city's hard infrastructure, including its drainage system, and increasing flood risk (Fig. 4). As with the import of Coyoacán's spring water 600 years earlier, the adaptation to augment the water supply with a new source, in this case groundwater, proved maladaptive for managing flood risk. In 1940, city managers finally responded to the growing problem of subsidence by implementing a moratorium on groundwater pumping near former lakebeds. Pumping continued, however, in areas surrounding the city until all pumping in the Federal District was banned in 1954, ending this decision cycle. Only then did subsidence abate.

Fig. 4. Water pumping, imports, exports, and subsidence rates from 1900-2010 with key flood (red arrows) and water supply (green arrows) adaptation interventions. Sources: Durazo and Farvolden 1989, Marsal 1992, Ezcurra et al. 1999, Romero Lankao 2010, Aguilar-Barajas et al. 2015.



The year 1952 marked the beginning of a fifth cycle. In response to the city's growing water demand largely due to industrialization (Aboites Aguilar 2009), the federal government decided to import groundwater from the Lerma watershed in the neighboring State of Mexico, in attempt to slow subsidence and end the city's dependence on local groundwater. Through the elaborate new system of pumps and aqueducts, the city became yet again dependent on a water source external to its political boundaries as demand continued to grow and the city expanded. A supply-side focus on drinking water management was sustained, and engineers considered water imports indispensable to cope with population growth (González Reynoso 2016).

In the 1970s, the sixth cycle began with the city and federal government once again confronting growing water demand by importing water and drilling more wells. Water managers rejected proposals for water treatment and reuse that would increase water efficiency and conservation. Instead, starting in 1982, they decided again to import surface water, this time from the more distant Cutzamala watershed (Castro 2006, OCAVM 2010). As in the time of the Mexica, these transfers generated social conflict and political resistance (Perló Cohen and Gonzalez Reynoso 2005), but the city soon was dependent on these external sources for 30% of its supply. Importing water became increasingly expensive and inefficient: the system consumes enormous amounts of energy to pump water uphill and subsidence has damaged the infrastructure, leading to leaks and water losses. Consequently, imports from the Lerma system have fallen from 15 m^3/s in the 1950s to under 5 m^3/s today (Delgado-Ramos 2015).

Still, importing water from nearby watersheds did not have the desired effect of reducing local groundwater dependency. In the throes of a severe drought in 1974, the government lifted the moratorium on groundwater extraction and increased the number of wells. The decision was also politically motivated: the dominant political party, the *Partido Revolucionario Institucional* (PRI), stood to gain votes in Mexico City in an upcoming election by solving the water crisis (Davis 2010). The wells that the government drilled in the south of the city, initially as part of a temporary emergency action plan (or PAI, its Spanish acronym) to avoid water shortages, remain active to this day, supplying ~9% of the city's water (OCAVM 2010).

Finally, a new decision cycle for water management began in the late 1980s in recognition of the city's dependence on groundwater and the threat that urbanization of the watershed poses for aquifer recharge. In 1992 the city government established the Conservation Zone. The urban government also created soft infrastructure, i.e., land-use regulations and rural development programs, to protect the watershed from degradation, deforestation, and urbanization. This decision can be interpreted as the latest iteration of urban authorities' efforts to manage water by dominating the communities that surround the city. Over 70% of land in the Conservation Zone belongs to indigenous and agrarian communities (Gobierno del Distrito Federal 2012), which are now severely limited in their land use, resource use, and opportunities for economic development because of the city's conservation policies.

Some demand-side initiatives were also launched during this time. In the 1980s, campaigns to increase water efficiency in the home were launched, the most recognized of which being the *Ciérrale* (turn it off) program in 1983 (Torres Hernández 2014). In 1989, low flow toilets were retrofitted in large office and apartment buildings, saving the city 0.8 m^3/s, just over 1% of total demand (National Research Council et al. 1995). Other traditional demand-side initiatives, such as increasing water tariffs to discourage use, have proven to be not only unpopular and difficult politically (Villalobos Guerrero et al. 1982, Villareal and Villareal 2006), but also difficult to implement because just over half of the city's water users are metered (National Research Council et al. 1995).

Today, the city continues to rely on supply-side water-management strategies. In its 20-year plan, the city water authority details how it could continue this adaptation pathway with new deep wells and water transfers from as far as the state of Veracruz (SACMEX 2012*a*; see https://www.gob.mx/conagua/prensa/expertos-presentan-estrategias-hidraulicas-en-materia-de-agua-para-el-valle-de-mexico), even though investments in increasing efficiency in the current system could yield great gains in supply (SACMEX 2012*a*). The city loses 30-40% of its current water supply to leaks, resulting from both aging built infrastructure and hundreds of thousands of clandestine taps (Tortajada 2006). In addition, an unknown quantity of water is illegally pumped from the basin's aquifer for industrial agricultural irrigation in the State of Mexico, as well as for private industries that sell it to water-scarce neighborhoods via documented clandestine wells (IDB 2012). The public sector has failed to address these issues or implement more demand-side management strategies. The challenges of managing water scarcity and water quality have thus been passed to citizens, who have adapted by investing in water storage and purchasing privately bottled water (Eakin et al. 2016). Mexico is now the second largest consumer of bottled water in the world, with Mexico City alone consuming more than three million cubic meters of bottled water annually (Delgado-Ramos 2014). Discarded plastic bottles contribute to flood risk as they accumulate in drains and waterways, restricting water flow (Delgado-Ramos 2015).

Drainage and flood risk pathway

Awareness of the city's vulnerability to flooding came as early as 1382. In the first major decision cycle around 1446, the Mexica, led by Nezahualcóyotl, decided to separate Lake Texcoco from the city center with the basin's first dike system. This flood-mitigation investment reduced the frequency of flood events and, by separating saline and freshwater, it allowed both agricultural expansion and population growth (Sanders 1976). The dikes, however, created new vulnerabilities for the food system: when Texcoco's waters overtopped the dikes, they destroyed crops and caused famines (Cruickshank 1998, García Acosta et al. 2003). Despite the dike system, floods repeatedly affected Tenochtitlán, provoking other innovative infrastructure investments (SACMEX 2012*b*). Drainage from the enclosed endorheic basin was not technically feasible or desirable: despite risks, the lakes were considered an asset essential for food, transportation, defense, and other services.

The Spanish, in contrast, considered the lakes a source of flooding and disease (Córdoba 2004). They had little interest in using or conserving the lake waters over the long term, given their reliance on large haciendas for food and horses for transport (Aguilar Santelises et al. 1997). Thus the second major decision cycle to define this pathway began in 1555, following major floods, with the idea of draining the lakes even as the Mexica dikes were being rebuilt (García Martínez 2004).

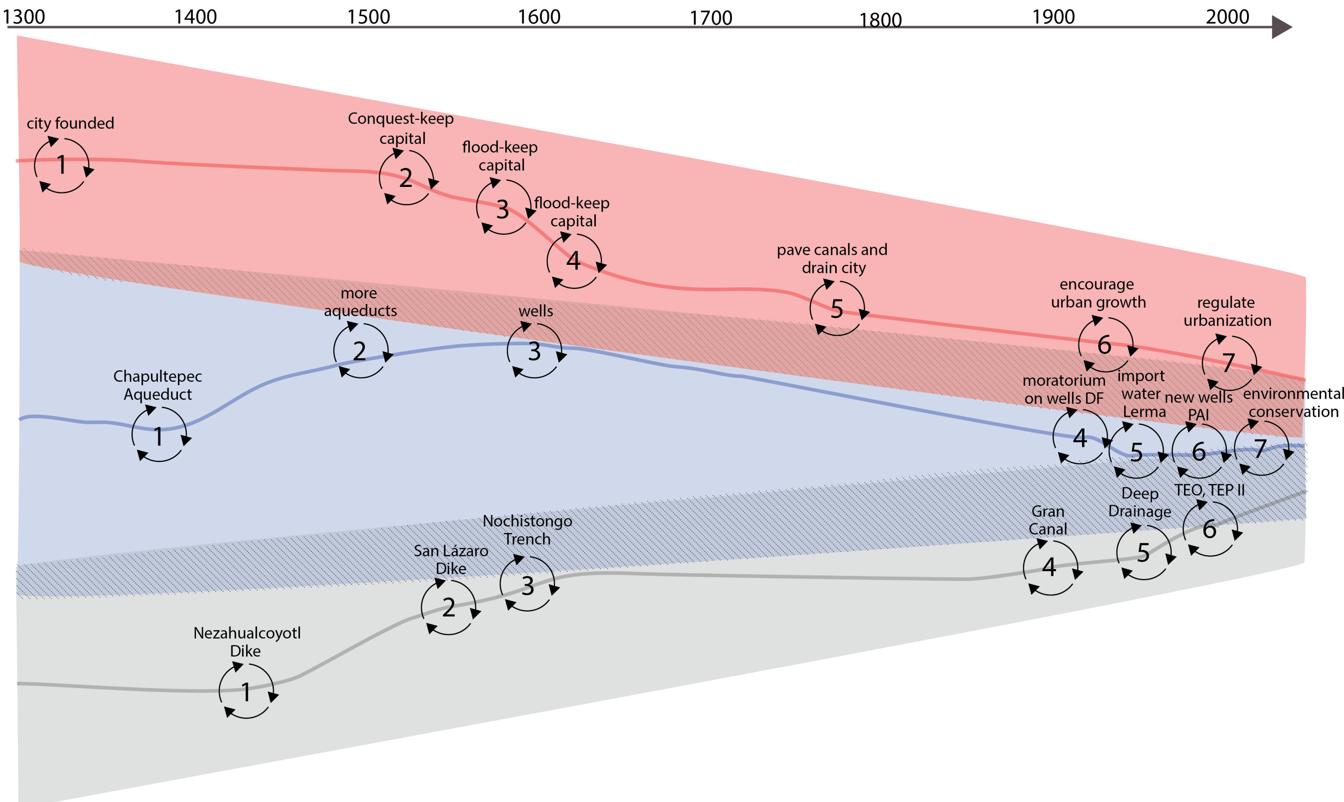
The third decision cycle centers on an action taken in 1607, when Viceroy Luis de Velasco Segundo implemented *El Desagüe* (The Drain), which exited via an artificial outlet carved through the mountains, the *Tajo de Nochistongo* (Nochistongo Trench). This was a monumental endeavor, especially considering the technologies available at that time, and it established the city's pathway for flood management thereafter. However, the trench's cost, slow construction, maintenance needs, and technical difficulty eventually embroiled it in controversy. The Spanish Crown's support began to waver, and it considered moving the colonial capital instead (Candiani 2014). In response, Viceroy Marqués de los Gélves stopped the trench's construction in 1623 and allowed the powerful Cuautitlán River to run its natural course into the valley, displaying a tragic ignorance of local hydrology. The Cuautitlán River had been a major source of flooding since the city's founding. The Mexica managed its powerful seasonal flows with diversions starting in 1433 (Candiani 2014). Marqués' decision led to the devastating floods of 1629 (García Martínez 2004). After the authorities committed to rebuilding rather than relocating the city, trench construction was revived, taking 165 years to complete and claiming 200,000 workers' lives (Connolly 2007). The trench partially drained the basin's lakes, significantly altering the CIS. Although it was intended to be the definitive solution, flooding continued to plague the city (García Martínez 2004, Hernández and Staedtler 2004, Legorreta Gútierrez 2008, Candiani 2014).

Following Mexican Independence from Spain (1821), in 1856, the authorities resolved to drain Lake Texcoco, the repository for the city's sewage and trash (SACMEX 2012*b*). In a fourth decision cycle, the government selected a design by engineer Francisco de Garay: a gravity powered canal, tunnel, and outflow ditch to drain the lake out of the basin to the neighboring state of Hidalgo (Agostoni 2003). But, they were prevented from implementing the plan by political instability and war (see Zoraida Vázquez 2013). The city coped with flooding by raising streets and floors in some areas, but this exacerbated flooding in lower-lying areas (Johns 1997). City residents became desperate for a solution, having suffered chronic floods and frequent epidemics. Drainage became associated with public health, modernization, and political glory (Johns 1997, Agostoni 2003). "By the mid-1880s decision makers in the city had one thing on their minds: 'The drainage project,' wrote the papers, 'is of the most transcendental importance for the city... it is a matter of life or death for residents of the Valley of Mexico.' 'The government that stops the floods, ' predicted one critic, 'will go down with glory in our history; and the man who heads it will be adorned with an immortal laurel wreath.'" (Johns 1997:44).

Finally, with the political and financial stability of the 30-year dictatorship of Porfirio Díaz (1876-1880, 1884-1911), the authorities were able to implement Garay's plan. With Mexico's approaching centennial celebration (1910), the project became a symbol of Mexico's progress and stability (Johns 1997, Agostoni 2003). The Díaz administration named the canal portion the Gran Canal (Great Canal). Like the Nochistongo Trench before it, the Gran Canal was to be the definitive solution to the city's flooding problem (DDF 1975), and it became an example of "how technical solutions could be devised to control the city" (Agostoni 2003:22). Over time, however, the outcomes for politics and water management played out quite differently than expected. Shortly after the centennial celebration, the stability of the Díaz dictatorship crumbled because of its corruption and inequality, giving way to the violent Mexican Revolution (1910-1920). And, the implementation of Garay's design ultimately exacerbated subsidence and flooding. In the next decades, millions of rural Mexicans migrated to Mexico City for new factory jobs and urbanized the newly drained land (Figs. 2, 3; Sheinbaum Pardo 2008). This urbanization drastically curtailed aquifer recharge, accelerated subsidence rates, and increased the city's water demand, requiring more groundwater extraction (Figs. 4, 5).

By 1950, subsidence prevented the Gran Canal from draining by gravity and began to exacerbate one of the very problems it was meant to solve: flood risk (Marsal 1992, Johns 1997). That year, a devastating flood struck the city, marking a fifth decision cycle. The city government admitted the Gran Canal was no longer sufficient for the city's drainage needs and had become a continual threat not only to the city's sinking historic center, but to the

Fig. 5. Timeline of three interacting adaptation pathways for Mexico City: human settlement (red), flood risk (gray), and water supply (blue). Major decision cycles for each pathway are outlined, and they overlap over time (see shaded/hatched areas). We conceive of the width of shading in each pathway as its adaptation space. This space has narrowed over time with efforts of city managers to increase system robustness. As a result, the system risks becoming maladaptive as it moves toward the boundary of the adaptive space, with less flexibility in responding to stress. The adaptation space for each pathway overlaps over time, as increasing system complexity, feedbacks, and connectivity ensure that decision cycles for one pathway influence the adaptive space in other pathways.



massive populations that settled along the canal's boundaries (Aragón-Durand 2009, SACMEX 2012*b*). In 1975, the city government embarked on another permanent solution: the Deep Drainage System (*Drenaje Profundo de la Ciudad de México*), designed to be a robust adaptation to subsidence. At the project's inauguration ceremony in 1975, urban officials framed the Deep Drainage System as a contribution to the preservation of the city's cultural and historical heritage, and linked it with the legacy of engineers and political leaders involved in water management throughout the city's history. Mexico City Mayor Octavio Sentíes Gómez declared:

> *This drainage follows centuries of work, and it is well known that our ancestors, the indigenous, had the same worries, to resolve the flooding problem... on repeated occasions we have said that we do not believe that public works are infinite, but in this case we affirm that the public work will be long lasting, for many years, and the Deep Drainage System will be a complete solution to all of the complex problems of Mexico City. Before, we said it was Nezahualcóyotl, then it was Enrico Martínez, then it was de Garay, and other engineers, other technicians that have worried about the water problem, and many generations have been constructing this drainage system... now the culmination of technicians, engineers, Mexican, workers, and others with heroic effort and even loss of life have made the work possible that is finally complete today...* (DDF 1975:257-260).

Subsequent flood disasters (1976, 1979, 1982, 1987, 1989, 1990, 1992, 1994, 1998, 1999, 2000, 2010), however, taught authorities that lack of redundancy in the drainage system produced more flood risk during drain maintenance. This lesson initiated the current decision cycle, beginning in 2008, in which the city government began construction of a new drain, the *Túnel Emisor Oriente* (TEO) or East Emission Tunnel, with massive financing that has increased over time. As of 2016, its current budget, 32 billion pesos, or 1.8 billion USD, is double the initial 2008 budget. The cost increases yearly (Páramo 2016). It has required complex new governance mechanisms for urban, interstate, and federal budgeting and coordination, mostly via the Mexico City Basin Commission (OCAVM). Despite these interventions in drainage, OCAVM estimates that if the main central drainage system failed today, the city center would flood up to 5 meters, and the flood footprint would cover 217 km².

Interconnected risks

Authorities' responses to the challenges and consequences of urban growth, water supply, and flood risk in Mexico City have defined adaptation pathways that have become interconnected over time, creating complex feedbacks among risk, adaptation, and vulnerability (Fig. 5). Over the 700 years of history we have summarized, authorities have enacted "definitive" solutions to threats that produce, often decades later, new risks and, inevitably, the same risk but of greater magnitude. The responses of a city, a CIS, to environmental stresses are not deterministic. Though responses are often shaped by previous decision cycles and infrastructure investments, decisions are made by people with the agency and authority to act at critical moments.

Subsidence (an externality of groundwater extraction, the city's adaptation for maintaining its water supply) accelerated as authorities drained the lakes to reduce flood risk, enabling the subsequent urbanization of the former lakebed. Subsidence alters the slope of drainage pipes, decreasing built infrastructure efficiency and system capacity to both remove water from the basin in floods as well as deliver drinking water to consumers, exacerbating both water scarcity and flood risk. Subsidence requires expensive energy investments to maintain water import and export capacity. Pumping water into the basin and the city from Lerma and Cutzamala, as well as pumping sewage and flood water out of the basin, consumes a great deal of energy (OCAVM 2010, Delgado-Ramos 2015). Despite extensive knowledge about subsidence, the inertia of the adaptation pathways to mitigate flood risk and water scarcity prevents mitigation of the fundamental causes and effects of subsidence.

Urbanization itself, by increasing demand for water and land, also reinforces feedback loops. As the city's demand for water grew, it inhibited aquifer recharge and exacerbated subsidence. Efforts to halt urbanization of the watershed and groundwater extraction within the Federal District have forced both urbanization and new groundwater extraction into the neighboring State of Mexico. What were once system externalities, e.g., the drying of springs of neighboring fiefdoms to satisfy Tenochtitlán's water demand and the exploitation of the Lerma watershed to supply Mexico City's water demand, are now endogenous problems engulfed by the expanding metropolitan area. Vulnerabilities are already apparent: in 2004, Mazahua communities, who live in Mexico City's import watershed of Cutzamala, disrupted the city's water supply system, demanding access to the drinking water exported to the city and reparations for flood damage to their crops caused by the dam infrastructure used to secure Mexico City's supplies (Wickstrom 2008). The same consequences of spatial externalities are also implicated in Mexico City's flood-risk management. The untreated wastewater that Mexico City exports to Hidalgo via the Gran Canal is used to irrigate food crops that are then sold and consumed in Mexico City, with the potential for causing food-borne illness (Mazari-Hiriart et al. 2001). The current plan, to build one of the world's largest treatment facilities to treat this wastewater, has raised concerns among Hidalgo farmers who rely on the nutrient-rich water for irrigation.

Efforts to control flooding through massive drainage projects have also led to maladaptive pathways. The combined sewage and storm water drainage system established in the nineteenth century is now stressed by subsidence and completely dependent on pumps. It contributed to two major sewage floods in the densely populated periurban district of Chalco in 2006 and 2010. Technological failures are now a significant threat to the city, causing the city's managers to focus on increasing redundancy through the construction of the new outlet, the TEO. This flood-risk solution also comes with trade-offs and risk transfers: engineers are now studying the possibility that the public works will export flooding to Tula, a small city in Hidalgo, on the banks of the river slotted to received TEO's waters (Carmona Paredes et al. 2014).

Most fundamental to Mexico City's interconnected risks was the decision to drain the lakes, first acted on over 400 years ago, in 1607. In 1985, a major earthquake struck Mexico City; all the buildings damaged by the earthquake were located on the ancient lakebed, which amplified the earthquake's waves (Flores et al. 1987, Rueda 2012). Draining the lakes allowed for urban expansion, economic growth, and flood protection, but also indirectly paved the way for the loss of 10,000 human lives and 3-4 billion USD in built infrastructure damage.

These are just a few examples of the "wickedness" of adapting to water risks in Mexico City. As the city's authorities have attempted to increase robustness of responses to environmental variability, this adaptiveness has increased vulnerability to less frequent but higher magnitude consequences of the same risk (e.g., flooding, drinking water scarcity), intensified the impacts of other, unanticipatedly interconnected risks (e.g., earthquakes), and produced vulnerability to unforeseen risks (e.g., subsidence).

DISCUSSION

Mexico City's story provides ample evidence for the claim that at any point in time, adaptation options are circumscribed by decision cycles and choices of the past. The city's history demonstrates the conundrum of robustness-vulnerability trade-offs: efforts to enhance system defenses against one set of threats inevitably generate new vulnerabilities to other sets of threats. The history also reveals several new insights that illustrate features of urban CISs and may provide guidance for contemporary efforts to manage urban risks, namely: (1) adapting to risk by externalizing it can backfire: as cities expand spatially and become more interconnected, such risks become endogenous; (2) over time, adaptation pathways initiated to address specific risks may begin to intersect, creating complex trade-offs in risk management (Tainter 1990); and (3) urban authorities contribute to the production and mitigation of risk through their management choices, which tend to focus on addressing external threats and expanding hard infrastructure systems. However, even in the face of new exogenous risks such as climate change, acknowledging and managing endogenous risks may prove more adaptive. Finally, Mexico City's water history underscores the political nature of adaptation and of system feedbacks (Eriksen et al. 2015). As Eriksen et al. (2015) argued, adaptation to environmental change takes place in social and political contexts of asymmetric power: decision makers choose what environmental signal or threat to respond to, when it matters and for whom, and how to respond.

First, although current conceptualizations of robustness-vulnerability trade-offs acknowledge the importance of transferring vulnerabilities across temporal and spatial scales, there have been few studies of specific cases and their implications.

Urban decision makers often adopt measures that externalize risks spatially, beyond city boundaries, engaging in what Cumming et al. (2006) referred to as "spatial subsidies." These decisions may reduce risk within urban boundaries in the short term, but they inevitably produce conditions that enable growth and spatial connectivity. As the city grows in size and complexity, the same risks emerge later and demand direct management. These unintended consequences are evident in Mexico City's history: city authorities imported water sources from beyond the city's physical boundaries starting in the pre-Hispanic period: they tapped the springs of the surrounding mountains, then local groundwater, then surface and groundwater resources of other watersheds. These supply-side adaptations permitted urban expansion (Mazari-Hiriart et al. 2001), which in turn not only increased water demand over time, but also expanded the spatial and political boundaries of the system that needed to be managed for the city's sustainability. Today, the Lerma Valley is the fastest urbanizing area in the sprawling megalopolis region with growing demand for its groundwater resources. This has led to groundwater overexploitation, subsidence, and flooding in Lerma (Perló Cohen and González Reynoso 2005). Urbanization and water demand have been exacerbated in the Lerma Valley and the State of Mexico as a whole because of regulations within Mexico City's boundaries that restrict urban expansion. Because Mexico City proper depends on water imports from Lerma, this urbanization ultimately affects Mexico City's choices for managing current and future water supplies.

The strategy of spatial subsidies, mediated by hard and soft infrastructure thus becomes maladaptive over time. As the CIS expands, its demand for resources, and therefore new spatial subsidies, increases, as is evident in other megacities. For example, the larger the city and the higher its GDP, the more likely it is to shift its water supply toward interbasin transfer. Seventeen of the world's largest cities import over 43% of their water (McDonald and Shemie 2014). Public infrastructure allows cities to make such adaptations, expand, and avoid conditions of collapse. However, the uneven social and monetary costs of these supply-side adaptations, both within city boundaries and the broader system from which it draws resources, should be considered. Soft infrastructure and new multiscalar governance arrangements become increasingly necessary to manage the social and spatial relations, as well as to respond to the emergent social and environmental risks engendered by this form of adaptation (Tainter 1990).

Mexico City adds to the growing set of case studies that illustrates the CIS framework, which highlights the spatial subsidies and growth of the system boundary that we assume is more typical of urban CISs than rural CISs. For example, the sunk cost of infrastructure investments in cities is much higher than a rural irrigation system, and efforts to keep the system functioning via spatial subsidies are likely much greater in an urban context. Although many CIS studies look at rural systems that eventually failed, modern urban systems force us to rethink collapse, or find new criteria that signal failure.

Second, Mexico City's history reveals how risks become interconnected, reinforced, and even created over time through city authorities' efforts to make the city more robust to a specific threat (Fig. 5). Adaptation to one type of risk influences the adaptation pathways to other risks. For example, the decision in the 1800s to combine drainage of storm water and sewage, a response to early erroneous notions of disease transmission (see Agostoni 2003), now impedes rainwater infiltration to the aquifer system, which exacerbates subsidence. Subsidence now affects the viability of the drainage network and increases flood risk. Storm water thus represents a real health threat when hard infrastructure failure results in floods. Ultimately, the progressive interaction of adaptation pathways and the consequent interdependency of risks in the CIS narrows the range of choices for adaptation, both in the present and future, because infrastructure systems are hierarchically nested. As investments are made over time, these nested subsystems become more interconnected and the overall system becomes more rigid, generating what resilience scholars call a rigidity trap in which institutions become "highly connected, self-reinforcing, and inflexible" (Gunderson and Holling in Carpenter and Brock 2008:40). Thus, from the perspective of coupled-infrastructure pathways, the interaction of system dynamics and human agency results in actors putting consecutive decision cycles into motion, which generates path dependency and lock in. Anderies et al. (2016) have called for more studies using the CIS framework to demonstrate the sequencing of infrastructure investment decisions and their dynamics over time.

The CIS framework is not intended to simply capture a snapshot of a system's structure at one moment in time. Rather, it is intended to help understand how existing feedbacks generate capacity to cope with both endogenous and exogenous variability and how these feedbacks also change the system's structure over time. Our long-term analysis of the case of Mexico City illustrates the sequence of infrastructure investments over several decision cycles, animating CIS dynamics over time in ways previous case studies have not. Mexico City also illuminates an understudied part of CISs: the political economy of infrastructure feedback. Often, adding capacity to the current hard infrastructure system is less costly in the short term, more predictable in outcome, and more in line with currently held perceptions on how to solve the immediate problem. An empirical basis for this logic is found in Mexico City's water management history by tracing how authorities learn about the consequences of past infrastructure investments and why and when new interventions are proposed. In so doing, this case study helps illustrate how to use the CIS framework to interpret dynamic change by providing several examples of how investment decisions generate feedback processes, new vulnerabilities, and subsequent investment decisions along the adaptation pathway.

Third, this historical approach highlights city managers' agency in defining the range of choices for adaptations in the future. Climate change has spurred cities to look toward the horizon and focus on new and potential exogenous stressors. An examination, however, of historical adaptation choices for that city and their impacts on risk(s) emphasizes that vulnerability is, in many ways, the product of endogenous factors. The history of Mexico City reveals how the decisions that have defined the city's development pathways were debated, what knowledge the city's authorities considered relevant, and what knowledge or feedbacks they dismissed: none of their decisions were inevitable. Their decisions ultimately shaped the built environment, the city's hydrology, topography, and land cover. However, in today's era of global climate change, we often fall into a discourse that defines threats as external to the system, thus distracting attention from the underlying vulnerabilities that the city produces itself, as a result of cumulative decisions in different spheres. We know, for example, that Mexico City's pattern of urbanization has increased the intensity of rain storms that cause urban flooding (Benson-Lira et al. 2016). City managers have blamed the city's smog in part on altitude, rather than on the decisions that led to industrialization and urbanization in the basin (Connolly 2007). The city's continual commitment to groundwater extraction is producing subsidence that weakens hard infrastructure and causes fissures in the soil, which have contaminated the city's aquifer with bacteria from wastewater (Mazari-Hiriart et al. 2001, Carrera-Hernández and Gaskin 2007). The decision to drain Lake Texcoco and urbanize the lakebed caused severe dust storms in the 1970s, which were eventually mitigated by a large ecological restoration project (Ezcurra et al. 1999). This project is now threatened by plans to build a new international airport over the restoration site. Climate change will undoubtedly produce new threats for cities like Mexico City and exacerbate existing vulnerabilities (Romero Lankao 2010), but addressing the existing endogenous sources of risk may ultimately be the most effective way to reduce urban vulnerability.

Finally, when city managers and inhabitants learn about social-ecological system dynamics, the learning is filtered through channels of authority, identity, and knowledge that are historically specific (Eriksen et al. 2015). Adaptation, and by implication, learning, is political. When Ahuizotl used his authority to implement his water supply plan, he ignored local knowledge, leading to the devastating flood of 1499. The Spanish colonial authorities' lack of, and disregard for, local knowledge in the Basin of Mexico resulted in the maladaptive decision to let the Cuautitlán River flow its natural course, culminating in the devastating floods of 1629. In 1856, local knowledge and authority aligned around the flood mitigation strategy of draining Lake Texcoco; however, unstable political conditions prevented its implementation. Thirty years later, scientific knowledge, authority, and political conditions aligned under the dictatorship of Porfirio Díaz, who executed that strategy, thus continuing the pathway of flood risk management via basin drainage.

The political nature of learning and adaptation is also apparent in the city's decisions regarding its water supply. Over the twentieth century, and arguably even earlier, the science and engineering community raised concerns about the region's ability to continue supplying water for an expanding population (Hiriart et al. 1952, Mazari 1996). Engineers have argued for developing other urban centers (Mazari 2000) and redesigning the city's water system to make use of recycled wastewater (Mazari Menzer 2001, 2004). However, supply-side solutions have dominated the water-supply adaptation pathway (González Reynoso 2016). Path dependencies inherent in the city's commitment to current water resources and the politics of water decision making have meant that these suggestions have been ignored, ultimately limiting choices for future water supply management.

Political and economic interests have also encouraged adaptation decisions that fill immediate needs but are ultimately maladaptive, though they are not perceived as such until time has passed and the consequences are evident. At several key moments after the Spanish Conquest, leaders seriously considered moving the capital after experiencing devastating floods and the 1985 earthquake. However, they always chose to stay, citing previous economic investments in urban infrastructure and property, and the political and religious authority embedded in the capital city.

More recently, the competitive 1976 election led authorities to expand the groundwater supply system to meet the city's growing water demand in exchange for votes. However, this politically expedient decision unraveled the moratorium on groundwater pumping, set by an earlier administration to mitigate subsidence. As a relatively slow onset problem, subsidence does not beget urgent responses or publicity, nor does it promise the same political benefits as hard infrastructure projects aiming to satisfy the city's immediate water demand. Indeed, there has been awareness of subsidence since the early seventeenth century, but very little direct action has been taken to address the problem aside from the 1954 well moratorium, which was revoked after only 20 years.

Clearly, one lesson from this history is that risk management and adaptation are not technocratic endpoints but dynamic social and political processes (Smith et al. 2011, Wise et al 2014). The Nochistongo Trench was the first of many "permanent" solutions to flood risk. In fact, Mexico City has invested in numerous new pumps and permanent drainage solutions since this first investment. The current "permanent" solution, the TEO, is already 15 years behind schedule and 100% over budget (Páramo 2016). Neither the TEO today, nor the Gran Canal in the 1800s, may have been required if the colonial authorities had not set Mexico City on a specific adaptation pathway over 400 years ago, with their decisions to destroy Aztec flood mitigation infrastructure, drain the basin, and fill the canals. Decision makers in the city have followed this path so narrowly that their actions and investments have caused rigidity and lock in. Today, if the city's decision makers fail to invest in maintaining and building new drainage works, the consequences will be devastating.

In this way, built infrastructure can be both an adaptation and an obstacle to system transformation. Hard infrastructure in particular provides a degree of robustness to specific risk responses that then sets a standard of where and how much disturbance (a flooded area, for example) a city is willing and able to tolerate (Liao 2012). Maintaining the robustness of the adaptation can require enormous public investment, and the ensuing hard infrastructure may further constrain urban adaptation pathways. As this infrastructure begins to fail, the cost of adaptation tends to be increasingly borne by individual households in marginal areas of the city (Eakin et al. 2016).

Thus, as cities become more complex over time, adaptation may require a radical reconceptualization of urban form and function, as well as an innovative way of treating water and reusing it. At what point is it maladaptive to invest in infrastructure to preserve urban form or protect specific zones, buildings, or properties from environmental change? If investments in infrastructure are inevitably maladaptive in the long term, is there anything city managers can do now to prevent losses later? At what point should cities explore alternative forms and/or pathways that may be more appropriate for changing social and environmental conditions? What are the trade-offs for urban identity and function? Doing more of the same and expanding existing infrastructure may be inadequate for sustainable adaptation in megacities (Mazari-Hiriart et al. 2001). Scenario planning and integrated risk management that consider potential consequences across a spectrum of urban risks may reduce the potential for maladaptation. Ultimately, however, as urban decision makers learn about the consequences of their efforts for risk mitigation, they must manage adaptation as a process in which outcomes are continually evaluated. Institutions that govern risk must evolve to maintain a good fit between institutional and biophysical dynamics (Anderies and Janssen 2013). Anderies and Janssen (2013) suggested that achieving this fit might depend largely on improving the relationship between public infrastructure providers (policy makers) and resource users (e.g., vulnerable citizens). Those who experience losses from flooding, scarcity, and disease firsthand have valuable knowledge of the dynamics of risk in their neighborhoods. This knowledge has not typically been part of Mexico City's supply-side and engineered solutions to water-related risk; they have pursued technically and politically oriented solutions.

The relationship between citizens and their governments will enable or constrain social learning and creative adaptation responses to conditions of high uncertainty. The expansion of risk, both in magnitude, quantity, complexity, and space that come along with urban growth requires an expansion of adaptation strategies and options. The adaptation pathways approach (Leach et al. 2007, Haasnoot et al. 2013, Wise et al. 2014) calls for opening up policy processes to allow wider participation and hence the inclusion of more ideas. The goal is to examine adaptation pathways that go beyond efforts to address risk incrementally and work toward mitigating underlying vulnerability. For example, by focusing exclusively on hard infrastructure solutions, decision makers can ignore the voices of ecologists, town planners, urban architects, and even local residents; exclusions that have proven problematic for sustainable water development in other cities (Rijke et al. 2013). For Mexico City, importing water from new watersheds may be the most immediately viable and familiar way to increase robustness and, in the short term, provide the lowest-cost adaptation to water scarcity given the city's current pathway. However, other options, such as treating and reusing water or rainwater capture, may be cheaper and more appropriate in the long term, and may open up the water supply adaptation pathway to new trajectories of development (instead of narrowing it, as in Fig. 5). Such interventions as these do not (yet) have consequences that reverberate across other adaptation pathways.

CONCLUSION

It is evident that all adaptation trajectories today are constrained by choices made in the past. The accumulation of deliberate decisions, each made with or without available knowledge, and within particular political, economic, and cultural contexts, creates the range of choices we have today. Past decision cycles ultimately give shape to the boundaries and dynamics of the current coupled infrastructure system, its exposure to risk in the present and future, and the choices available today. Though we cannot keep all options on the table (ultimately choices have to be made with available information and resources), documenting how we have arrived at today's options, including the pathways that were not pursued and the reasons why, may provide insights into the consequences of our choices for tomorrow. Ultimately, history demonstrates that our very best solutions today may present critical challenges for tomorrow, and that collectively, people have far more agency in and influence over the complex systems we live in than we often acknowledge.

Urban adaptation that relies on expanding existing hard infrastructure may be cheaper, predictable, and more comfortable in the short term, and can provide job security and other benefits to decision makers. However, the agency to break this path dependency and pursue options on new adaptation pathways could be leveraged in urban systems and provide cost savings in the long run. In pursuing adaptation, we are constantly creating and redefining the boundaries of the systems we live in, the risks we face, and the future choices we have, as well as sustainability for future urban habitants.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/9712

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